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Evolution and prediction of the La Niña conditions in 2024/25

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Keywords: arrested development of La Niña conditions, equatorial easterly winds, ENSO regime shift, prediction failure

Abstract

Skillful El Niño–Southern Oscillation (ENSO) prediction is one of the most important problems in climate science due to its substantial global impacts. There have been many successful examples of predicting ENSO using dynamical climate models since the mid-1980s. It was therefore unexpected that many operational climate models significantly overestimated the likelihood of La Niña conditions in 2024. In this report, we examine the physical processes associated with the arrested development of La Niña conditions in 2024/25, and the possible reasons for overestimated predictions of its strength. Despite favorable subsurface cooling conditions following a strong 2023/24 El Niño, we argue that arrested development of La Niña conditions in 2024/25 resulted from weak episodic easterly wind anomalies and associated weak upwelling Kelvin wave activity, which failed to shoal the thermocline sufficiently to initiate basin-wide air-sea coupling. Furthermore, we find that weaker Kelvin wave activity and ENSO amplitude reduction were linked to the ENSO regime shift with strengthened mean zonal sea surface temperature contrast and enhanced mean trade winds in the tropical Pacific around 2000. Model limitations in capturing atmospheric variability and interdecadal shift contributed to the overestimated strength of the La Niña predictions in 2024/25, underscoring the importance of properly simulating atmospheric variability and the interdecadal regime shift in dynamical models used for predicting ENSO.

1. Introduction

El Niño–Southern Oscillation (ENSO) is the most important source of global climate predictability on seasonal-interannual time scales (e.g., Rasmusson and Wallace 1983, National Research Council 2010, McPhaden *et al* 2020, Hu *et al* 2020a). ENSO prediction has been a major research objective since the breakthrough work of Bjerknes (1969) with the first successful prediction of an El Niño using a dynamical model in 1986 (Cane *et al* 1986). Today, operational ENSO monitoring and forecast systems have been a centerpiece of many climate services, such as the National Oceanic and Atmospheric Administration's National Centers for Environmental Prediction (NOAA/NCEP; Hu *et al* 2022, L'Heureux *et al* 2024), and the National Climate Center of China Meteorological Administration (Ren *et al* 2018).

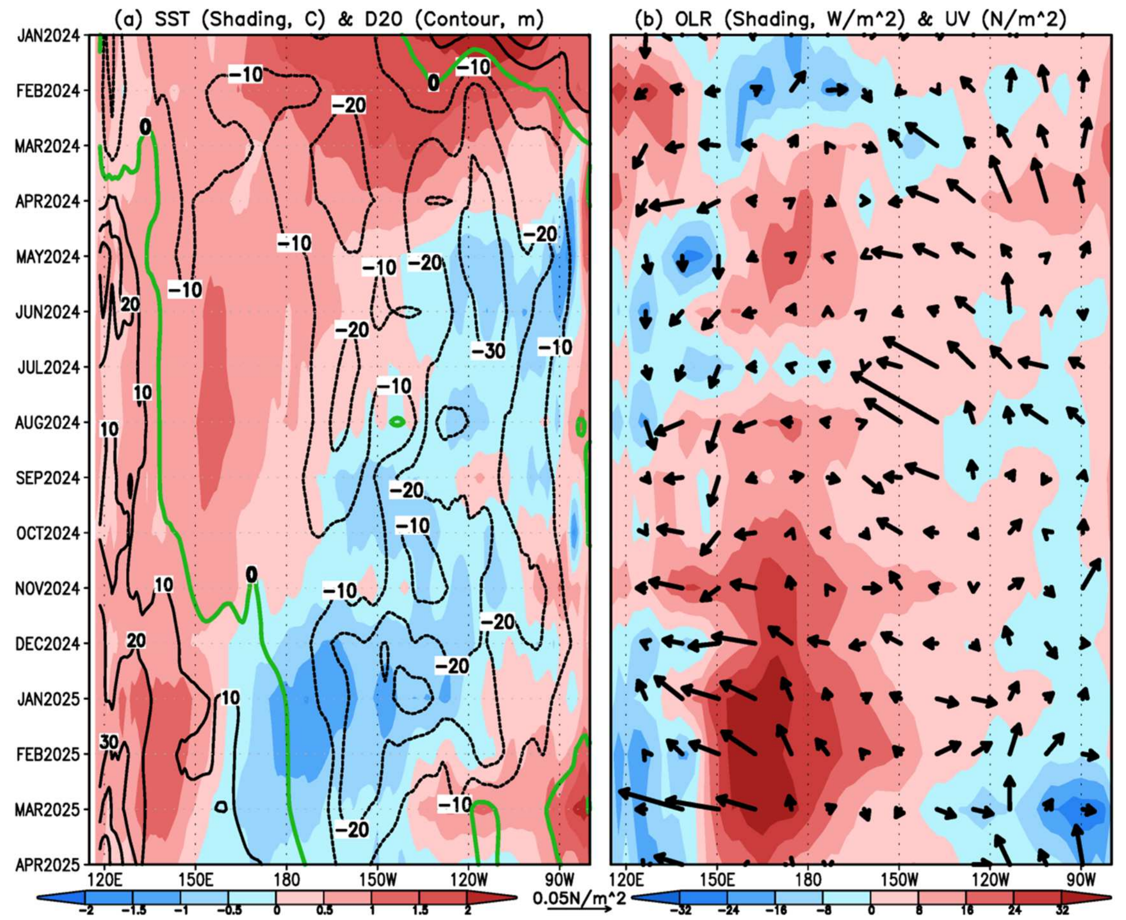

Figure 1. Hovmöller diagrams of the monthly mean of (a) SST (shading; °C) and D20 (contours; m), and (b) OLR (shading; W/m^2) and surface wind stress (N/m^2; black vectors) anomalies averaged in 2°S-2°N during January 2024 - April 2025.

La Niña conditions developed in the boreal winter and spring of 2024 (figure 1) with observations showing negative sea surface temperature anomalies (SSTA), an unusually shallow thermocline, suppressed convection and positive outgoing longwave radiation (OLR) anomalies in the eastern and central equatorial Pacific, and enhanced convection together with negative OLR anomalies in the western equatorial Pacific. Consistently, anomalous low-level zonal winds were mostly easterly in the central equatorial Pacific at this time. After the strong El Niño in 2023/24 (Tan *et al* 2024a; figure 2(b)), a La Niña of substantial amplitude was anticipated based on recharge oscillator dynamics (Jin 1997, Meinen and McPhaden 2000, Wang and Picaut 2004, Wang 2018, Planton *et al* 2021, Vialard *et al* 2025). According to the recharge oscillator dynamics, after an El Niño, the equatorial Pacific is in a heat-discharged condition, favoring a phase transition to La Niña. However, despite favorable antecedent subsurface cooling in the tropical Pacific in the wake of the strong 2023/24 El Niño (figure 1(a)), the anticipated duration and amplitude of Niño3.4 SSTA La Niña conditions did not materialize (figure 2(b)).

The purpose of this study is to address the important question of what caused the unexpected evolution of the La Niña conditions in 2024/25 and to assess the real-time predictions. The data and methods used in this work are introduced in section 2. In section 3, we analyze the evolution of the zonal wind anomalies in the tropical Pacific and wind-forced Kelvin wave activity in 2024/25. Moreover, it has been documented that interdecadal variations of ENSO may modulate its predictability (e.g., Ye and Hsieh 2006, Jiang *et al* 2020). Specifically, around 1999/2000, ENSO has shifted to a regime with higher frequency and smaller amplitude events compared with that in 1979–1999 (McPhaden 2012, Hu *et al* 2020b), which contributed to a decrease in seasonal prediction skill (Barnston *et al* 2012). Therefore, we also discuss the influence of the ENSO regime shift around 1999/2000 on the evolution and predictability of conditions in 2024/25. With that background, we assess model predictions in 2024/25 and examine their shortcomings in section 4. A summary and discussion are provided in section 5.

2. Data and methods

We use monthly mean Optimum Interpolation SST v2.1 (OISSTv2.1; Huang *et al* 2021) on a $1^\circ \times 1^\circ$ grid since September 1981. This product is computed from the daily OISSTv2.1 that incorporates observations from

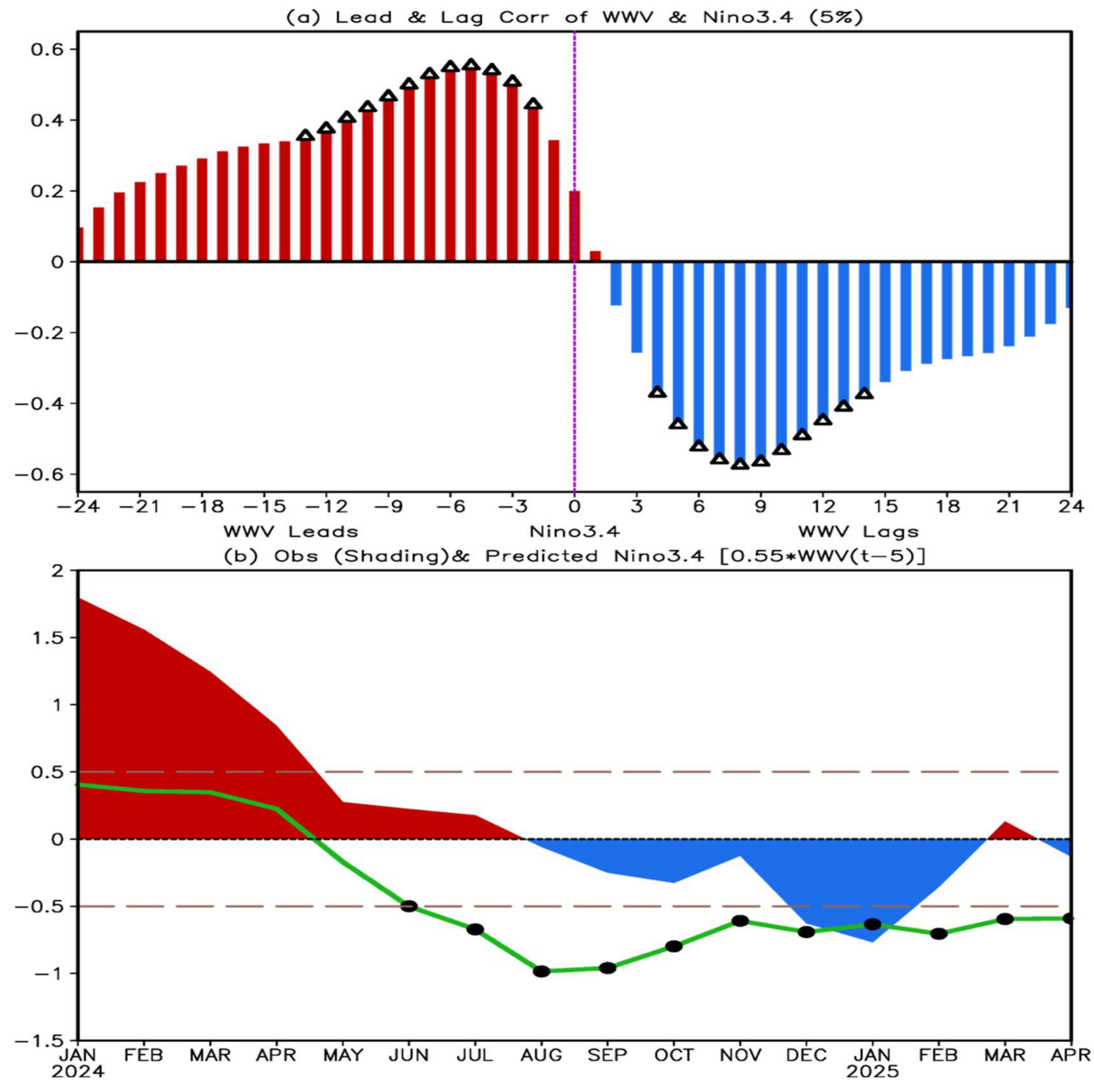

Figure 2. (a) Lead and lag correlations between the Niño3.4 and WWV indices in January 1982–December 2023. The negative (positive) numbers along the *x*-axis denote the number of months of the Niño3.4 index lagging (leading). The bar with triangles denotes significant correlations at the 5% significance level using a t-test with independent sample size estimation (Bretherton *et al* 1999). (b) Monthly mean of the observed (shading) and predicted (green line) Niño3.4 index (°C) during January 2024-April 2025. The two horizontal dashed lines in (b) represent 0.5 °C and −0.5 °C. The predicted Niño3.4 index is computed based on equation (1). The predicted values indicated by closed circles in (b) are less than −0.5 °C.

different platforms (satellites, ships, buoys, and Argo floats) into a regular global ¼ ° by ¼ ° grid. ENSO is represented by the Niño3.4 index (the SSTA averaged in 5°S−5°N, 170°W−120°W; Barnston *et al* 1997, Li *et al* 2023a). The classification of ENSO events follows the NOAA/CPC's definition, and the Oceanic Niño Index (ONI) is from the NOAA/CPC webpage (https://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php). An El Niño (La Niña) is defined when the ONI is larger (smaller) than 0.5 °C (−0.5 °C) for a minimum of 5 consecutive overlapping seasons (L'Heureux *et al* 2024). ONI is 3-month running mean of the Niño 3.4 index, based on centered 30-year base periods updated every 5 years.

Recharge/discharge processes in the equatorial Pacific (Jin 1997) are associated with the cyclic evolution of ENSO and represented by the warm-water-volume (WWV) index, defined as the monthly mean anomalies of the depth of 20 °C isotherm (D20) averaged in (5°S−5°N, 120°E−80°W) (Meinen and McPhaden 2000). A normalized Kelvin wave index (Seo and Xue 2005) is calculated using pentad ocean temperature of the upper 300 meters along the equatorial Pacific between 135.5°E−94.5°W, based on an extended empirical orthogonal function analysis. A positive (negative) index represents downwelling (upwelling) Kelvin wave activity, favoring El Niño (La Niña) development.

The monthly mean D20 and surface wind stress, and pentad surface zonal wind stress are derived from the Global Ocean Data Assimilation System (GODAS; Behringer 2007). GODAS is forced by momentum flux, heat flux, and freshwater flux from the NCEP-Department of Energy Reanalysis 2 (R2; Kanamitsu *et al* 2002).

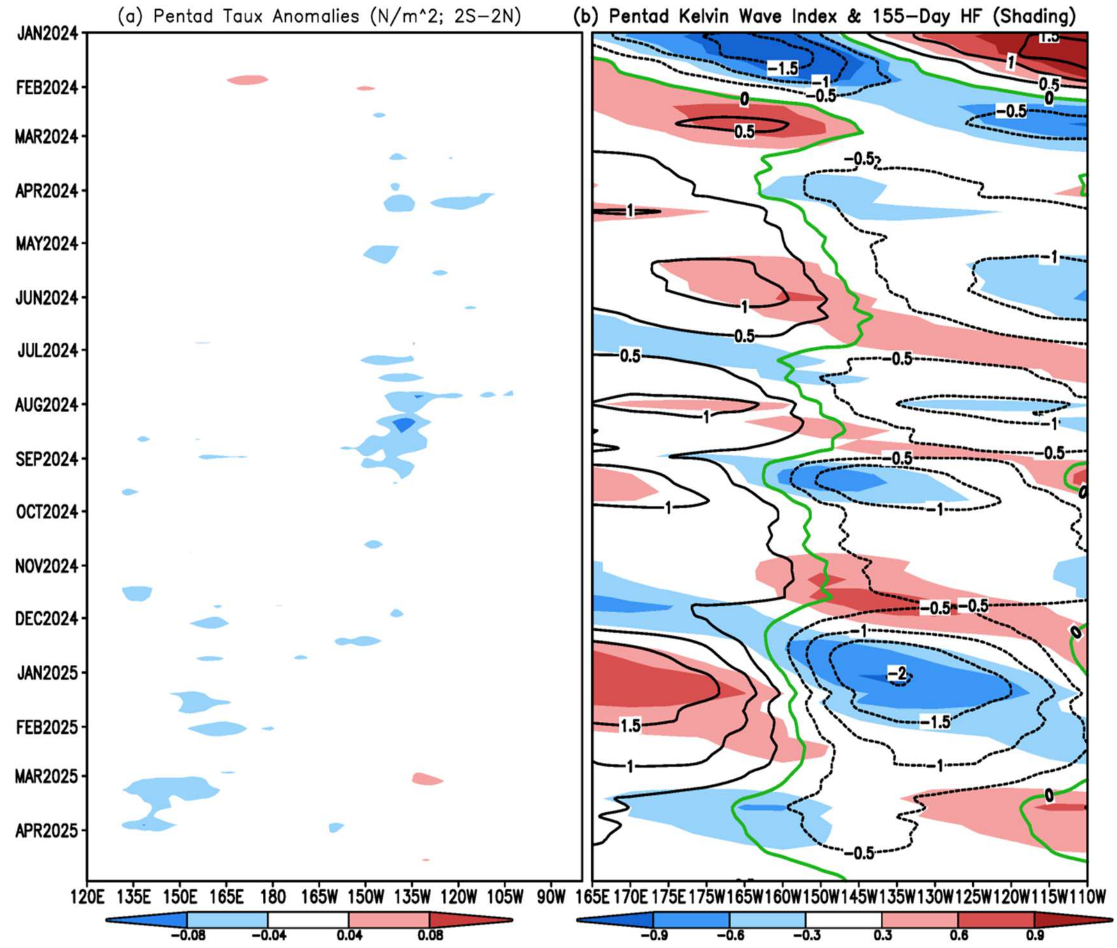

Figure 3. Hovmöller diagrams of (a) pentad mean zonal wind stress anomalies averaged in 2°S-2°N with amplitudes larger than 0.04 N m^{-2} plotted, and (b) normalized pentad oceanic Kelvin wave index (contours) during January 2024 –April 2025. To eliminate the stationary component and low-frequency variations in the Kelvin wave index, a high-frequency pass-filtered index with the 155-day running mean removed is displayed in shading in (b). A negative (positive) Kelvin wave index implies an upwelling (downwelling) Kelvin wave.

Tropical deep convection activity is measured by monthly mean OLR on a 1°× 1° grid from January 1974 onward (Guo *et al* 2024). The OLR data are the NOAA/CPC blended level-2 OLR retrievals.

To assess the prediction skill of ENSO in climate models, we use predictions from the North American Multi-Model Ensemble (NMME; Becker *et al* 2022). The six models are the NCEP Climate Forecast System version 2 (CFSv2), the National Aeronautics and Space Administration NASA_GEOS5v2, the National Center for Atmospheric Research NCAR_CCSM4, the Geophysical Fluid Dynamics Laboratory GFDL_SPEAR, the Environment and Climate Change Canada CanCM4i, and GEM5_NEMO. The predictions (hindcasts and real-time predictions) start from January 1982 to the present, with lead times extending to 9 months. The numbers of ensemble members for the six models vary from 4 to 20. CanCM4i and GEM5_NEMO were retired in August 2024, and their replacements did not have real-time predictions with initial conditions before September 2024. All model specifications have been detailed in Becker *et al* (2022; see their table 1). The OISSTv2.1 is adopted as observations in verification.

Monthly and pentad anomalies in the observation-based analyses or reanalysis, and in the NMME predictions, are computed as the departures from their respective climatologies over 1991–2020. The statistical significance of correlations is tested using the Student's two-tailed t-test at the 5% significance level with independent sample size estimations according to Bretherton *et al* (1999).

3. Observed anomaly evolution in 2024/25 and possible interdecadal modulation

As a precursor for ENSO evolution (Kug *et al* 2005, McPhaden *et al* 2006, Tseng *et al* 2017, Neske and McGregor 2018), based on the lead-lag correlation between the Niño3.4 and WWV indices in 1982–2023 (figure 2(a)), we can use the normalized WWV index to forecast the ENSO evolution in 2024/25 with the

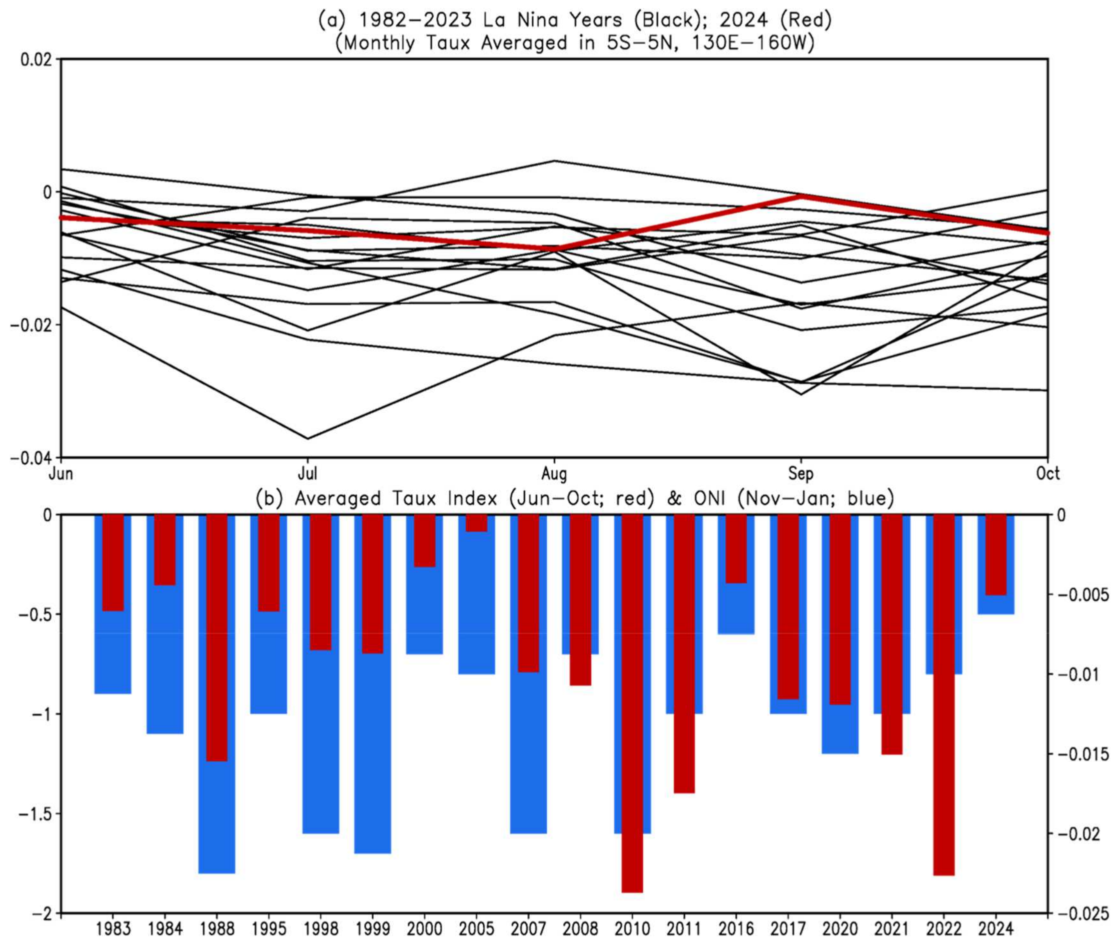

Figure 4. (a) Monthly zonal wind stress anomalies (zonal wind index) averaged in (5°S-5°N, 130°E-160°W) in June -October in La Niña developing years during 1982–2023 (black lines) and in 2024 (red line). (b) November-December-January (NDJ) ONI (blue bar; left *y*-axis) and the zonal wind index averaged in June-October (red bar; right *y*-axis) in La Niña years and 2024.

following equation:

$$\text{Niño3.4(t)} = 0.55 * \text{WWV(t}-5) \quad (1)$$

Where Niño3.4 is in units of °C. The forecasts (green line in figure 2(b)) called for a La Niña event of substantial amplitude peaking in August-September 2024 according to the ENSO event definition at NOAA's Climate Prediction Center (NOAA/CPC). The La Niña did not develop as expected (figure 1(a)), we explore the possibility that its arrested development may have been due to the weakness of intraseasonal atmospheric surface wind anomalies, and associated Kelvin wave activity. Abrupt zonal wind pulses, either westerly wind bursts or easterly wind surges (EWS; Chiodi and Harrison 2015), can force eastward propagating equatorial Kelvin waves that perturb thermocline depth to affect the evolution of ENSO, especially in the developing phase of ENSO events (e.g., Luther *et al* 1983, Harrison and Vecchi 1997, McPhaden 1999, Wang *et al* 2011, Puy *et al* 2016, Neske and McGregor 2018).

According to Puy *et al* (2016), zonal wind stress anomalies must be strong enough, with a magnitude of at least 0.04 N m^{-2}, and last for at least 5 days to trigger Kelvin waves. The value of 0.04 N m^{-2} is approximately two standard deviations of the equatorially averaged zonal wind stress anomalies. Here, we refer to the pentad wind stress anomalies along the equatorial Pacific with values smaller than −0.04 N m^{-2} as an EWS. From figure 3, we can see the connection between EWS and Kelvin wave activity. For example, EWSs between April and early May 2024 and between early July 2024 and early September 2024 (figure 3(a)) were associated with some upwelling Kelvin wave-like thermocline fluctuations (figure 3(b)). However, during spring–autumn 2024, the pentad easterly wind anomalies were weak overall, as was upwelling Kelvin wave activity. Notably, EWSs mainly occurred in the eastern equatorial Pacific during this period, while pentad wind stress was near normal in the western and central equatorial Pacific. The Kelvin wave response to episodic zonal wind forcing depends on the strength and zonal fetch of the winds (Kessler *et al* 1995). The relative weakness and small zonal fetch of significant EWSs in 2024 resulted in weak upwelling Kelvin waves, which were unfavorable for

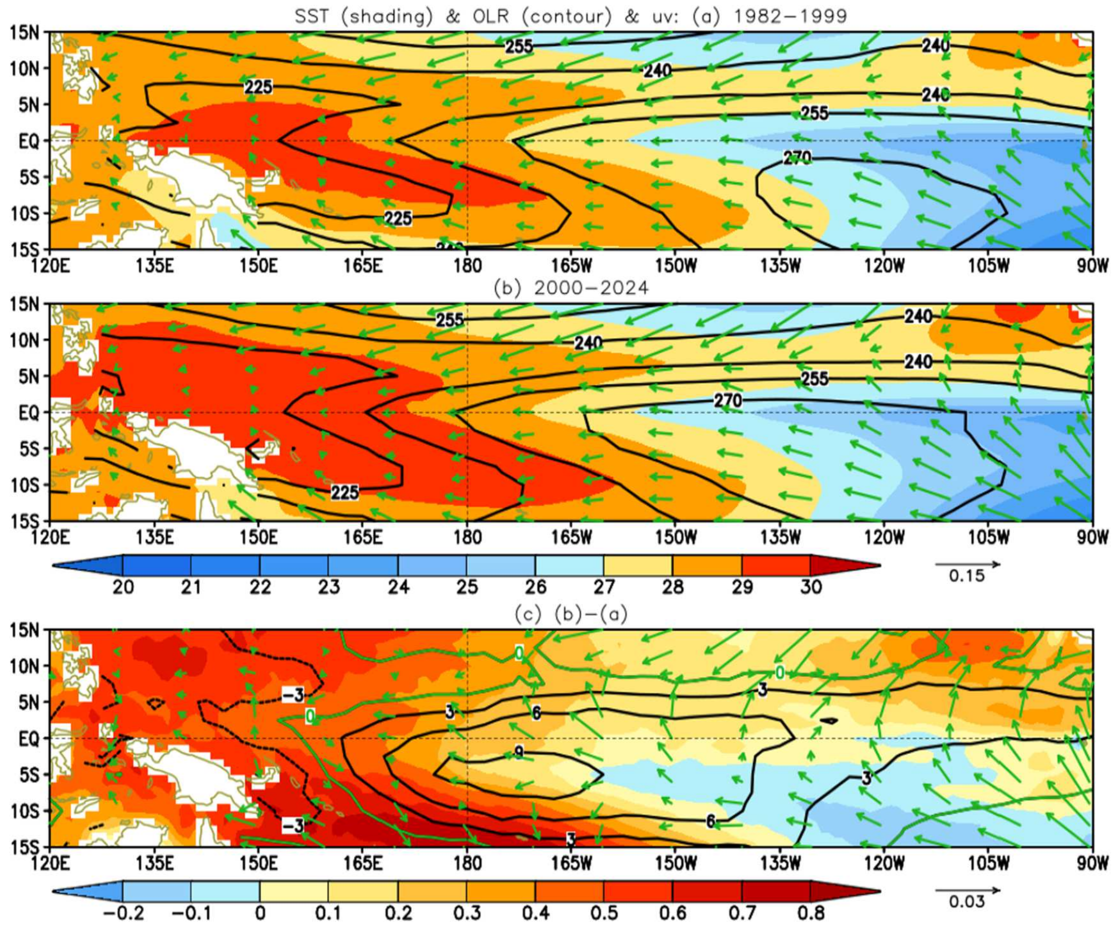

Figure 5. Monthly mean SST (shading;°C), OLR (contours; W/m^2), and surface wind stress (N/m^2) averaged in (a) January 1982—December 1999, and (b) January 2000—December 2024; (c) are the differences of (b)—(a). Contour interval is 15 W m^{-2} in (a, b), and 3 W m^{-2} in (c).

initiating the basin-wide air-sea coupling. Hu *et al* (2012) argued that wind pulses in the western and central equatorial Pacific are more favorable for ENSO growth than those in the eastern equatorial Pacific.

As a result of overall weak upwelling Kelvin wave activity during the spring–autumn 2024 (figure 3(b)), there was little tendency for further shoaling of the thermocline in the eastern Pacific to cool the ocean surface, unfavorable for La Niña development. A weak EWS in the equatorial western Pacific in November 2024 triggered an upwelling Kelvin wave, leading to a short period of cooling with Niño3.4 index = −0.6 °C in December 2024 to −0.7 °C in January 2025, but neutral conditions returned with Niño3.4 index = −0.4 °C in February and 0.1 °C in March 2025 (figure 2(b)). The weak pentad EWS (figure 3(a)) is consistent with weak monthly mean easterly wind stress anomalies (figure 4). An index for monthly mean zonal wind stress anomalies (average in the western equatorial Pacific between 5°S-5°N, 130°E-160°W) was weaker in 2024 than in most of the La Niña years during the June-October development phase of ENSO events (figures 4(a), (b)).

Interestingly, one can see from figure 4(b) that the ONI (blue bars) was relatively strong compared to the zonal wind index (red bars) before 2008, and relatively weak after 2008, implying that ENSO event strength since 2008 was less sensitive to wind stress anomaly forcing in the western equatorial Pacific than before 2008 (figure 4(b)). This is consistent with strengthening trends in zonal wind stress and zonal SST contrast along the Pacific equator in recent decades (Li *et al* 2023b) with strong warming trends in the tropical western Pacific/warm pool and minor cooling trends in the southeastern tropical Pacific/cold tongue (figure 5).

These results suggest that background conditions may modulate upwelling Kelvin wave activity. For instance, compared with 1979–1999, Kelvin wave activities in both upwelling and downwelling phases are weaker in 2000–2024 (figure 6) when the mean easterly wind stress is stronger and the zonal SST gradient is larger (figure 5). This is consistent with the westward shift and suppression of deep convection variability since 2000 (figure 5(c); Hu *et al* 2012, 2020b, Lübbecke and McPhaden 2014). Li *et al* (2019) and Tan *et al* (2024b) noted a weakening of Kelvin wave activity since 2000 associated with the ENSO regime shift around 1999/2000 (McPhaden 2012, Hu *et al* 2013, 2017, 2020b). Tan *et al* (2024b) further argued that in the context of a stronger zonal SST contrast and enhanced trade winds since 2000, Kelvin waves have weakened, which implies a less

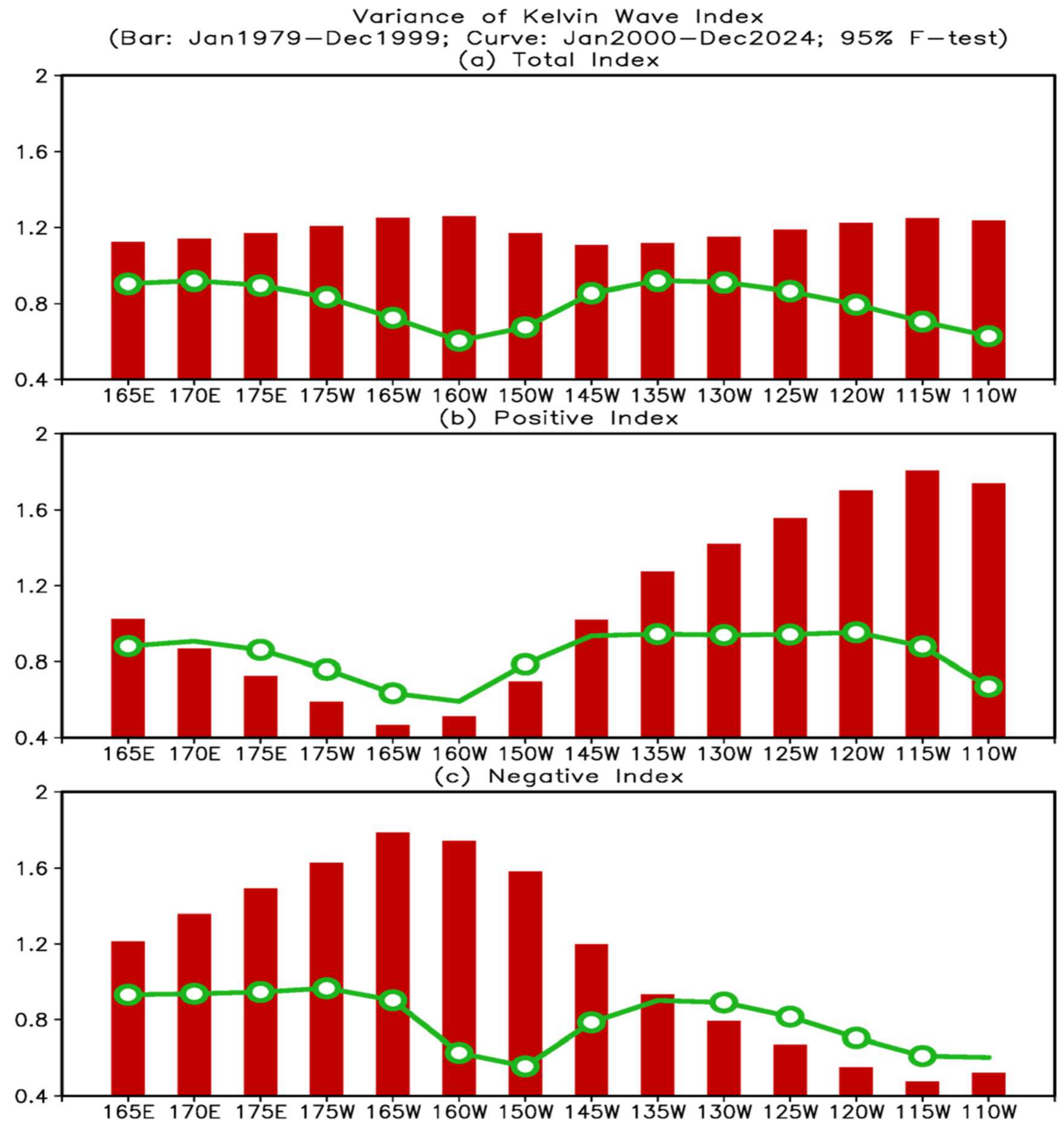

Figure 6. Longitude–dependent variance of pentad oceanic Kelvin wave index averaged in 1979–1999 (bar) and in 2000–2024 (curve) for (a) total index, (b) positive phase, and (c) negative phase. The curve with a circle indicates when the change of the variance is significant at the 5% level, using an F–test based on 1,000 Monte–Carlo resamples. Updated from Tan *et al* (2024b).

active role for them in the development of ENSO events. Similarly, Harrison and Chiodi (2009) suggested that enhanced equatorial easterlies contributed to a change in ENSO characteristics for the decade following the 1997/98 El Niño. Associated with these background changes, Kelvin wave activity is likely related to the asymmetry in the surface wind stress response to SSTAs during periods of prolonged cold versus prolonged warmth along the equator in the tropical Pacific. This in turn is related to the nonlinear response of atmospheric convection to SSTAs in which colder SSTs suppress convection and lead to weaker wind changes for a given SST perturbation (e.g., Liu *et al* 2024, Puy *et al* 2016, Chiodi and Harrison 2015).

4. Shortcomings in model predictions

To verify the predictions in the period from El Niño decay in 2023/24 to the growth of La Niña conditions in 2024/25, we display the ensemble mean predictions of the NMME models at specified lead times (5 and 8 months in figures 7(a), (b)), and 20-individual members from CFSv2 predictions with initial conditions (ICs) in April and July 2024 (figure 8). For the ensemble mean, among the six models in NMME, five models predicted a transition from a strong El Niño in 2023/24 to a La Niña with a peak at the end of 2024, while GFDL_SPEAR called for a borderline La Niña in 2024/25 (figures 7(a), (b)). The weak cooling in the

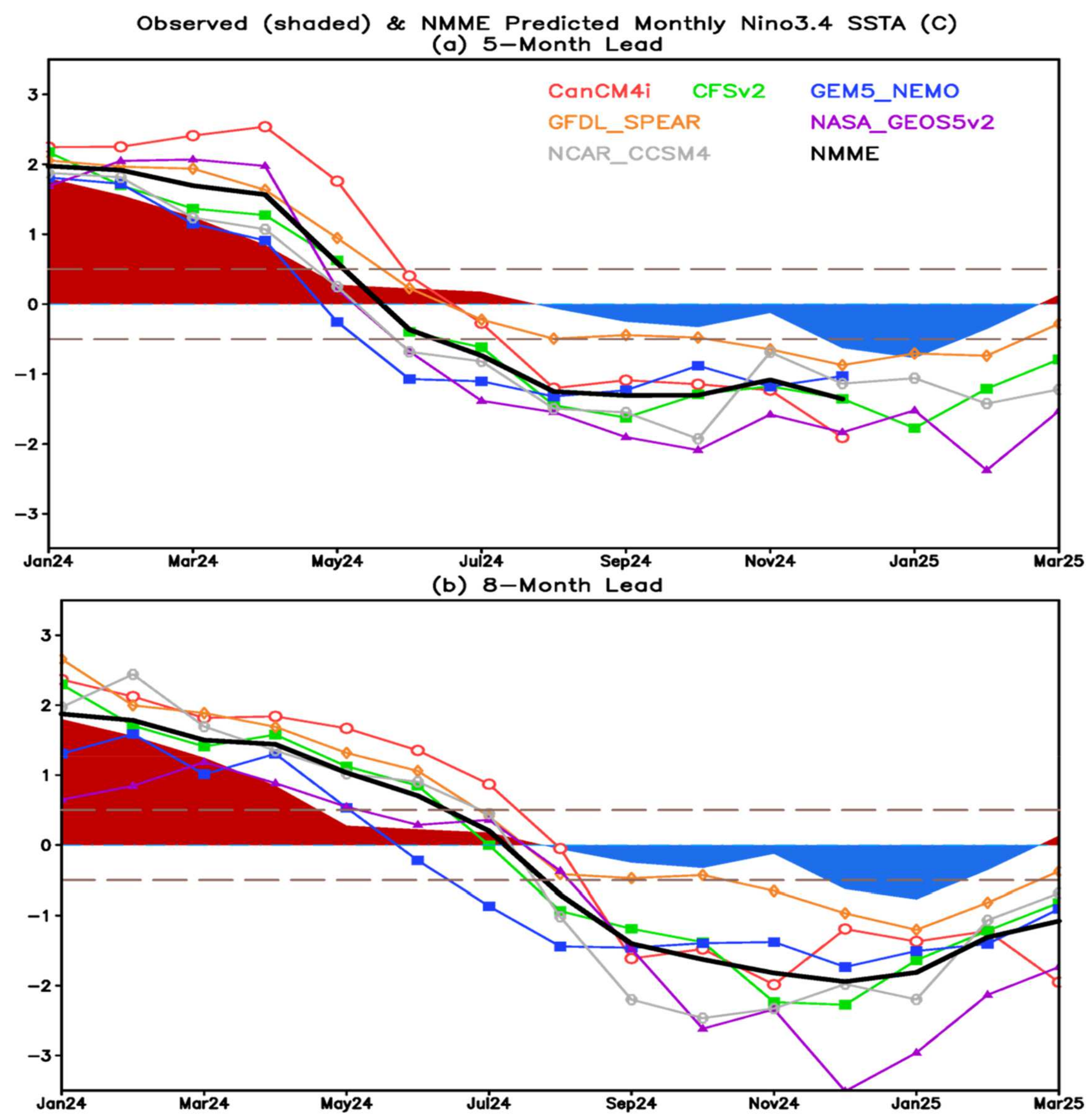

Figure 7. Observed (shading) and NMME model-predicted (lines) monthly mean Niño3.4 index (°C) in January 2024-March 2025 with lead times of (a) 5 and (b) 8 months of the six models and their mean (black line). The two horizontal dashed lines represent 0.5 °C and −0.5 °C.

GFDL_SPEAR predictions might be partially associated with warm biases in SPEAR ENSO predictions (Li *et al* 2023b).

It is clear that the ensemble means from a majority of the NMME models do not capture the observed evolution of the La Niña in 2024/25 (figure 7). However, individual ensemble members are close to the observations, like, for example, some members in CFSv2 predictions with ICs in July 2024 (figure 8(b)). On the other hand, all members with ICs in April 2024 are clearly distant from the observations (figure 8(a)), which may be associated with the impact of the spring predictability barrier. ENSO forecasts are intrinsically more uncertain or less skillful when starting prior to and during the Northern Hemisphere spring. This is a crucial challenge for ENSO cycle prediction (Hu *et al* 2019). Thus, from a probability perspective, the departure of most members in the CFSv2 predictions from observational means that the observed evolution of the ENSO in 2024/25 was a low-probability outcome for the ICs based on this model.

We further note that the over-forecasted Niño3.4 SST cooling is associated with too strong easterly wind anomalies, particularly for the predictions with ICs in April 2024 (figures 8(a), (c)). The correlations between the Niño3.4 index (blue bar) and zonal wind stress anomalies (red bar) among 20 members are 0.93 for ICs in April 2024 averaged in May 2024-January 2025 (figure 8(e)), and 0.77 for ICs in July 2024 averaged in August 2024-April 2025 (figure 8(f)). Furthermore, the easterly wind biases link to strengthened SST gradients in the tropical Pacific with warm (cold) biases in the western (central and eastern) tropical Pacific (figure 9). These biases lead to overestimated La Niña strength. That may also suggest that the cyclic transition from El Niño to La Niña in 2024/25 in NMME model predictions was dominated by oceanic heat recharge/discharge processes

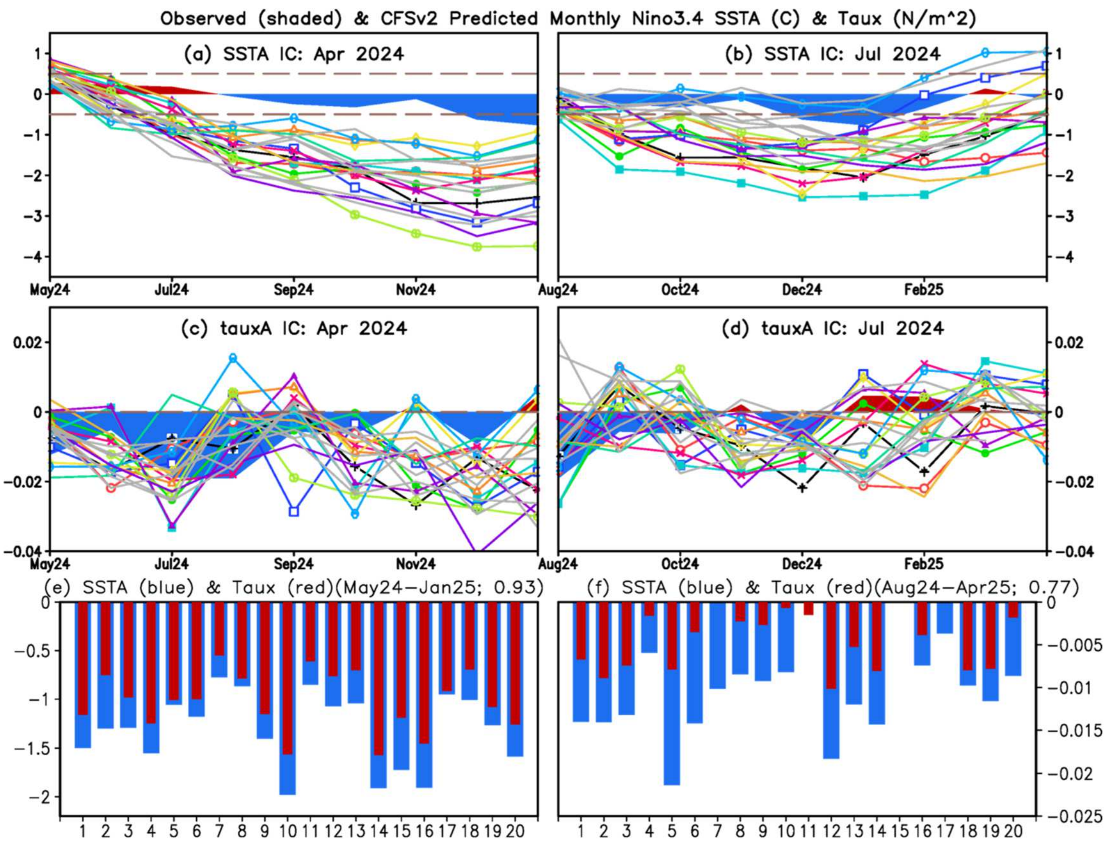

Figure 8. Observed (shading) and 20 individual members of CFSv2 predictions (lines) of (a), (b) the Niño3.4 index (°C) and (c), (d) zonal wind stress anomalies averaged in the Niño3.4 region with ICs in April and July 2024, respectively. Mean of each individual member (*x*-axis) of the Niño3.4 index (blue bar; left *y*-axis) and zonal wind stress anomalies (red bar; right y-axis) averaged in (e) May 2024-January 2025 and (f) August 2024-April 2025, respectively. The same color with the same mark in (a, c) or in (b), (d) represents the same ensemble member. The two horizontal dashed lines represent 0.5 °C and −0.5 °C in (a), (b).

(Jin 1997, Meinen and McPhaden 2000, Planton *et al* 2021). However, in addition to these large-scale oceanic conditions, intraseasonal atmospheric fluctuations, including the Madden–Julian Oscillation (MJO) and episodic wind bursts, also play an important role in ENSO evolution and prediction (McPhaden *et al* 2006, Gushchina and Dewitte 2011, Wang *et al* 2011, Lybarger *et al* 2020). It is possible that the El Niño to La Niña transition was interrupted by unfavorable atmospheric fluctuations or noise, as demonstrated in the divergence of CFSv2's members of the predictions (figure 8), as happened in the case of the aborted El Niño in 2014 (McPhaden 2015). Recently, Hu *et al* (2024) suggested that, in addition to the essential role of equatorial ocean heat recharge, multi-scale interactions from a global perspective also played a role in the evolution and prediction of the El Niño in 2023/24.

5. Summary and discussion

With noticeable antecedent subsurface cooling after the strong El Niño in 2023/24, a La Niña event of substantial amplitude was expected from the perspective of the recharge/discharge paradigm. However, the ensemble mean predictions of many operational climate models suggested that the event would be much stronger than it actually occurred. Why the La Niña did not grow as anticipated and what caused the strength to be overestimated in model predictions is an important question.

We know that upper ocean heat content is a necessary but not a sufficient condition for the development of ENSO events (Zhang *et al* 2022) and that stochastic forcing is also important from both theoretical (Levine and Jin 2010) and observational (McPhaden *et al* 2006, Hu *et al* 2019) perspectives. Sub-seasonal wind bursts are unpredictable on seasonal-interannual time scales, representing an unpredictable element of ENSO seasonal evolution. The interplay between these two elements, the predictable deterministic slowly evolving subsurface ocean heat content and the unpredictable stochastic wind forcing, determines the evolution and predictability of ENSO. We also noted that the episodic easterly wind anomalies were mostly in the eastern equatorial Pacific and also too weak to generate energetic upwelling Kelvin wave activity. As a result, the transport of cold

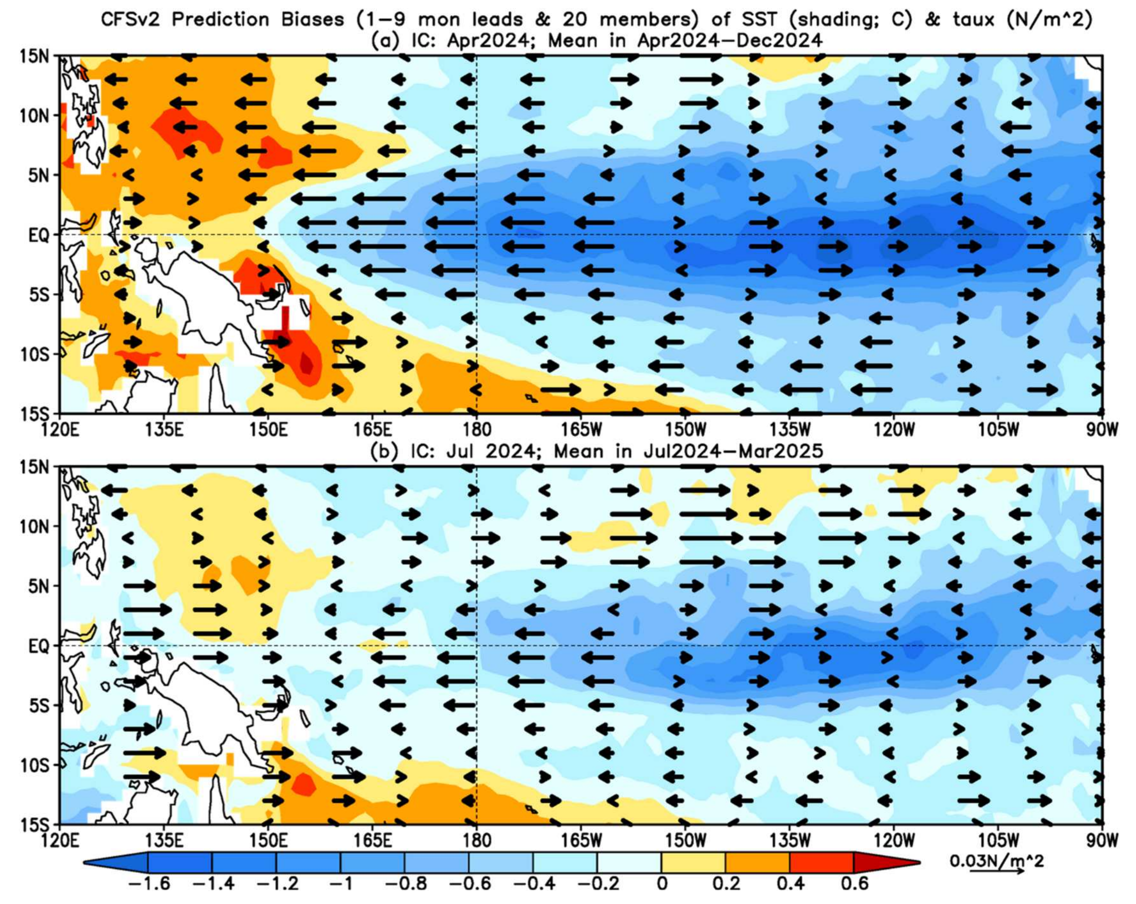

Figure 9. Biases of SST (shading; °C) and surface wind stress (vector; N/m^2) anomalies in CFSv2 predictions with ICs in (a) April 2024 and (b) July 2024. The observations are the averages in (a) April 2024-December 2024 and (b) July 2024-March 2025. The CFSv2 predictions are the averages of 20 ensemble members and 1–9 month leads.

subsurface water to the ocean surface was insufficient to trigger a basin-wide air-sea coupling via the Bjerknes feedback, inhibiting ENSO SSTA growth.

Moreover, background or mean state changes modulate ENSO evolution and contribute to the arrested growth of the La Niña conditions in 2024/25. In particular, after the regime shift in 1999/2000, intraseasonal Kelvin wave activity along the equator in the Pacific was weaker and thermocline variability was suppressed (Tan *et al* 2024b), which would contribute to weaker ENSO amplitude variability(Hu *et al* 2012, 2020b) and a weaker La Niña in 2024/25. In addition, biases in most NMME models to predict the observed cooling in 2024/25 may therefore also be associated with the changes in ENSO properties and predictability across the early 21st-century tropical Pacific regime shift. That is consistent with the decline of the ENSO prediction skill since 2000 (Barnston *et al* 2012, Hu *et al* 2020b).

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Conflict of interest

The authors declare no competing interests.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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